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Design of a Prosthetic Hand with Remote Actuation*

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Abstract— **One of the main issues of prosthetic hands is to be able to fulfill all the specifications about speed, torque, weight and inertia while placing all the components within the prosthetic hand. This is especially true when full dexterity is required in the prosthesis. In this paper, a new design for a prosthetic hand is presented, which uses remote actuation in order to satisfy most of those requirements. The actuators are to be located in the back of the subject and the transmission is implemented via cables. Other characteristics of this new prosthetic hand include torque limitation and the possibility of switching between underactuated and fully actuated functions.**

I. INTRODUCTION

The design of robotic prosthetic hands is a very active field of research. Recent research has focused on finding better actuation systems [1-4], integrating some compliance in the design [5-8], and generating better control strategies or input signals [8-10]. In addition to this, newer mechanical designs of fingers and hands are also being developed [5,6,11,12,13,14]. Some robotic hands that could be used for prosthetics are in an advanced design stage, such as DLR hand, i-Limb hand, Shadow hand, and fluidhand [2]. However, a prosthetic hand with all the properties desired by the users [15, 16] has yet to be achieved.

The main reason for the current state of hand prostheses is the complexity associated with the human hand, with its many actuators and sensors, which makes use of forearm muscles, nervous system, and body's energy generation system. Fitting all needed components within the physical size of the hand requires a degree of miniaturization that is still to be achieved.

There are two primary designs that are commonly used to specify how a robotic hand is actuated. Using one actuator for each degree of freedom produces a fully-actuated system. This approach allows maximum dexterity and manipulation, but often results in a bulky design requiring complex control algorithms and elaborate sensor modules for each degree of freedom. Underactuated systems, which require fewer actuators, have been known to adapt to variable environmental conditions without the use of sensors [17], [18], [19]. This approach simplifies the control algorithms by sacrificing hand function, strength, and the ability for the hand to adapt to the user.

The human hand has an average weight of 400 grams [20] (distal to the wrist and not including the forearm extrinsic muscles). However, prosthetic terminal devices of similar weight have been described as being too heavy by users [21]. This is primarily because the attachment methods between the prosthesis and the user compound the effects of the weight in the terminal device. Although researchers are currently working to alleviate attachment problems through the use of integrated attachment mechanisms, the weight of the prosthesis is a key contributor to interface discomforts and user fatigue [22].

In this paper, we explore two specific problems associated with robotic prosthetics: 1) the ability for the robot to adapt to the user and 2) the reduction in weight on ergonomics.

Our solution uses a remote-actuation, hybrid design, with an external multi-degree-of-freedom actuating system that can be switched from coupled actuation to full actuation.

A key performance of this hybrid design is to produce power grasps that passively make contact at multiple points, thereby providing the user the ability to apply the desired force on the object from multiple contact points. Due to the limited number of actuators and the uncertainty in object location and shape, the coupled actuation must be designed to minimize situations in witch not all links make contact with the object.

It is expected that the flexibility associated with this design will allow for a better adaptation to the many different types of amputees.

II. MECHANICAL DESIGN

A. Hand Structure

The overall shape and size of the hand is based on the average human hand. This includes five fingers and a thumb that are attached to a fixed palm. Revolute joints make up the 10 degrees of freedom for the interphalangeal (IP) joints of the fingers and IP and MCP joints of the thumb. Universal joints are used in the Metacarpals of each finger (MCP joints) and the CMC joint of the thumb, as well as the combination of flexion-extension and abduction-adduction of the wrist. These joint make up the other 12 degrees of freedom in this design. Joint actuation is created by a cable system that converts actuator rotational motion to linear motion and that back to rotational motion in the joint.

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To achieve the desired motion in a lightweight, durable construction, the hand components are made from thin gauge stainless steel. Individual links that makeup each finger and the thumb are created by bending thin gauge sheet metal into a tube like section that allow the finger pulleys, cables, and cable conduit to be discreetly hidden inside.

The palm of the hand is constructed in a similar fashion using shaped sheet metal as an external shell. Consecutive links are connected with 3 mm axle shafts that pass through ball bearings creating the revolute and universal joints. To drive the joint motion, 0.039 diameter Teflon-coated cables pass through 0.100 diameter cable conduit as it is roughed through each finger to the palm and then out to actuators located away from the hand. *Figure 1* shows the joint arrangement.

B. Joint Actuation

The linear actuation design in this paper operates with the use of a pull-pull cable system. Each joint is controlled by two cables that pass through cable conduits, from the actuator to the joint pulley. The actuator's rotational motion causes the pulley on the actuator to release cable on one side and draw cable in on the other. This results in a rotation of the joint pull and ultimately a rotation of the joint. In reverse fashion when the actuator rotates in the reverse direction the opposite cable is drawn or pulled in causing a tension in the cable and a reverse rotation of the joint pulley and the joint.

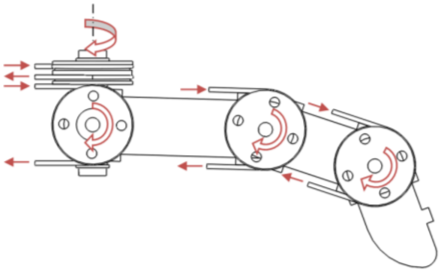

Figure 1: Finger Pulleys

This simple design is repeated for the Distal, Proximal, and Metacarpal joints of each finger and the thumb. However the metacarpal joints on each finger and the thumb are universal joints and add a second degree of freedom and a second pull-pull actuation cable system to the joint, see Figure 2.

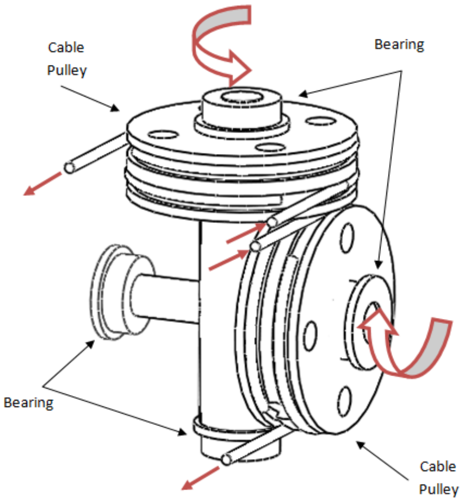

Figure 2: Metacarpal Universal Joint

The 2-dof wrist joint is also a universal joint, but a third rotational degree is added to allow hand pronation/supination. This results in 23 degrees of freedom. Because of the fact that the distal IP joints of a human hand on average are 70% coupled to the Proximal IP joints, the distal joint and the proximal joint of this design are actuated with one actuator resulting in a coupled motion for each finger. This coupling reduces the total independent degrees of freedom down to 19.

The cable conduit that is used to route the cable to the specific joint is a Bowden cable design and provides compression strength that is usually provided by the bones in the human hand. This allows thinner material to be used in the construction of the fingers and palm reduction weight that is felt by the user. The cables act as tendons that in this case are connected to actuators instead of mussels. A cable passing through a cable conduit can be seen in Figure 3. Notice that two cables are needed for each degree of freedom.

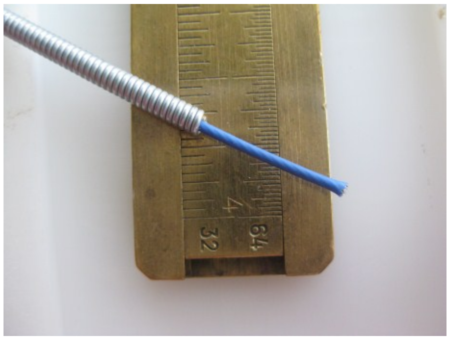

Figure 3: Cable conduit

III. ACTUATION SENSING

A. Faulhaber Actuation

To minimize the overall weight seen by the user, the actuators that control the hand motion are to be placed remotely, in an operational backpack. This allows actuators to be sized based on output power instead of overall dimensions. The power unit that is used to power both the control system and the actuators can also benefit from this design.

Figure 4: Faulhaber Gearmotor and Encoder

For each degree of freedom a Faulhaber Gear Motor and Encoder (Figure 4) will be used to drive the 19 active degrees of freedom. The windings have an overall resistance of 11 ohm, which means the motor will draw 0.55 amps at 6V if stalled. The motor has a peak efficiency of 74%. The no-load motor speed is 13,400 RPM at 6V but will be slower with a gearhead attached. **Error! Reference source not found.** shows the output shaft that connects to the actuator dive pulley. Resulting forces caused by tension in the cables will pass through the actuator mounting screws to the actuator mounting plate, then to the cable conduit.

The dual-channel encoder is similar to an HEM encoder that accepts a 4.5v to 15v. To measure only RPM or distance, the encoder has two channels, one of them providing one high pulse per revolution of the motor. There will be 141 high pulses per revolution of the gearshift, or about 2.55 degrees of final output rotation per pulse. To increase resolution or to measure rotation direction, the microcontroller can watch both channels A and B. The output of the encoder is very clean, see Figure 5.

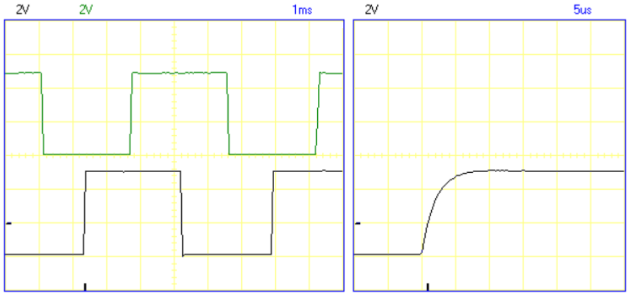

Figure 5: Oscilloscope trace of two channel encoder

To connect the gear motors to the individual finger pulleys, the pull-pull system described above is to be utilized. The routing of the individual cable conduits is yet to be developed.

B. Pressure Sensing

To provide tough/strength of grasp sensing in the hand, the actuator utilizes a variable resistance sensor. This sensor provides feedback to the controller of the toque being applied by the actuator to the finger. In simple control layouts the input voltage for the motor would pass through the variable resistor controlling the speed and stopping signal based on the spring constant. In more complicated controls this resistive signal would provide the force input that will allow one finger to provide more force then another and possibly create motion of object that have already been grasp.

This sensor is constructed by connecting a variable resistor to the dive hub and the motor pulley. A torsion spring connects the motor pulley to the drive hum. When force increased due to object contact, this force is carried through the actuation cables to the motor pulley and then into the torsion spring. As the spring stores this energy it allows the motor pulley to rotate on the drive hub and change the resistance in the variable resistor. This change in resistance provides feedback to the motor controller on the strength of grasp that the robot is producing. This sensor also provides a buffer to jerk that would otherwise be produced in the actuation system during grasp contact. A diagram of this sensor is shown in Figure 6.

One of the main benefits of using this type of tough/strength sensing is it allows for contact to be sensed no matter where it occurs on the robotic hand. Pressure sensors located at the tips of each finger have been used to provide similar sensing however if object contact does not happen in the unit normal direction this force can be misinterpreted by the sensor.

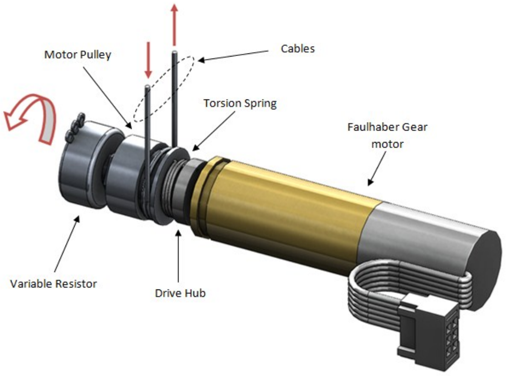

Figure 6: Pressure Sensor

IV. MOTION ANALYSIS

Because this design does not incorporate complex coupling linkages, the kinematics of the fingertip positions is relatively simple. Let R_1, R_2 and R_3 be the lengths of the phalanges and θ_1 to θ_4 be the joint angles for the four finger joints. The pose of the fingertip (point B) respect to point A can be expressed as a transformation, where the orientation of the fingertip is given by the quaternion

$$q = \begin{pmatrix} \sin(\frac{\theta_1}{2})\sin(\frac{\theta_2+\theta_3+\theta_4}{2}) \\ \sin(\frac{\theta_1}{2})\cos(\frac{\theta_2+\theta_3+\theta_4}{2}) \\ \cos(\frac{\theta_1}{2})\sin(\frac{\theta_2+\theta_3+\theta_4}{2}) \\ \cos(\frac{\theta_1}{2})\cos(\frac{\theta_2+\theta_3+\theta_4}{2}) \end{pmatrix} \quad (1)$$

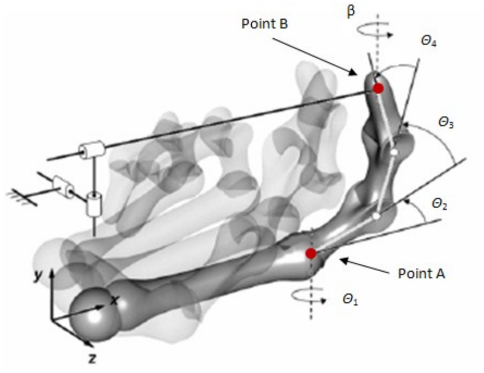

Figure 7: Joint notation

The location of point B referenced from point A is given by the vector

$$P_B = \begin{pmatrix} \cos(\theta_1)(R_1\cos(\theta_2) + R_2\cos(\theta_2+\theta_3) - (2(R_1+R_2)+R_3)\cos(\theta_2+\theta_3+\theta_4)) \\ R_1\sin(\theta_2) + R_2\sin(\theta_2+\theta_3) - (2(R_1+R_2)+R_3)\sin(\theta_2+\theta_3+\theta_4) \\ \sin(\theta_1)(-R_1\cos(\theta_2) - R_2\cos(\theta_2+\theta_3) + (2(R_1+R_2)+R_3)\cos(\theta_2+\theta_3+\theta_4)) \end{pmatrix}$$

Since θ1, θ2, and θ3 joints are controlled by their own independent actuator and θ3 and θ4 are coupled 1:1, the pose of the finger can be quickly determined.

V. PROTOTYPE

The prototype will be created using a sheet metal laser. Thin gauge stainless and sheet metal flat patterns created in Solidworks® CAD software (Figure 8) will allow each link in the hand to be created with an interlocking design that minimizes weight and maintains strength. This design also allows for simple maintains on the joint pulleys, cables, and cable conduits by allowing access to these areas without major disassembly.

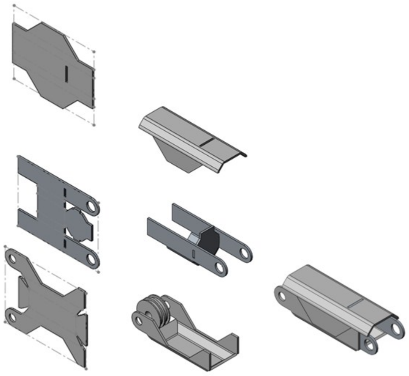

Figure 8: Sheet Metal Construction

The remaining palm and wrist of the hand will be constructed in similar fashion. Formed sheet metal stainless steel plates are joined together to form the bearing carrier for each metacarpal universal joint. The thumb of the hand is constructed the like each finger and connected to the palm plates with internal sheet metal bearing carriers. Structural strange of the system is achieved after all components are connected. This included the access plates that are used to maintain the actuation cables. Actuators for each degree of motion are mounted to a common mounting plate that is located in an operational backpack. A general layout of the actuators can be found in Figure 9.

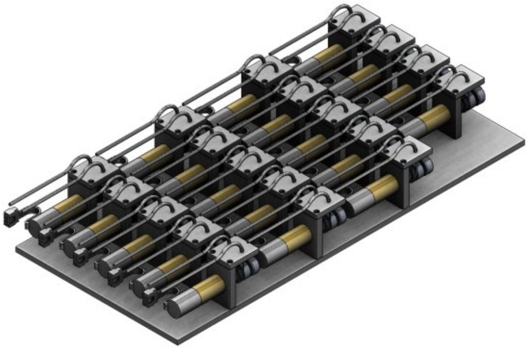

Figure 9: Remote Actuation

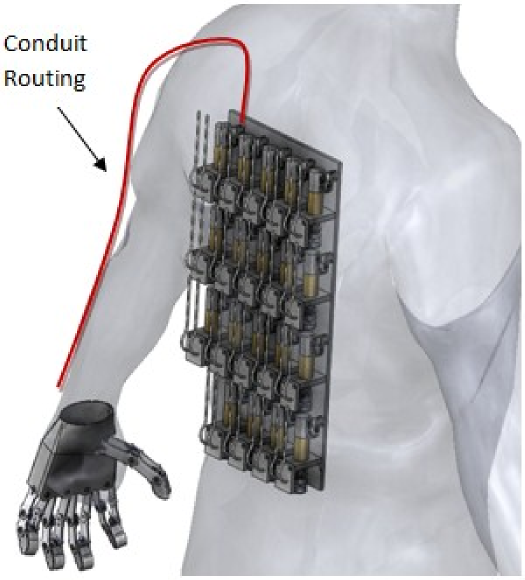

Figure 10: Conduit Layout

Cable conduit runs connect the robotic hand to the remote actuators that are located in the operational backpack. These conduit runs will attach the outside of the operators arm and follow the arm down to the hand similar to the sleeve on a shirt.

Figure 11: General Layout

The prototype is currently being built and will be used for testing the design.

VI. CONCLUSIONS

This paper presents a new design for a prosthetic hand. The design is based on remote actuation of electric DC motors via cables. This type of construction and design shifts the weight of the hand from the end of the prosthesis to a localized point closer to the center of mass of the user. This shift in weight is intended to reduce strain and fatigue on the operator during normal daily activities.

Future work includes the detailed modeling and simulation of the design, and the assembly and testing of the prototype.

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